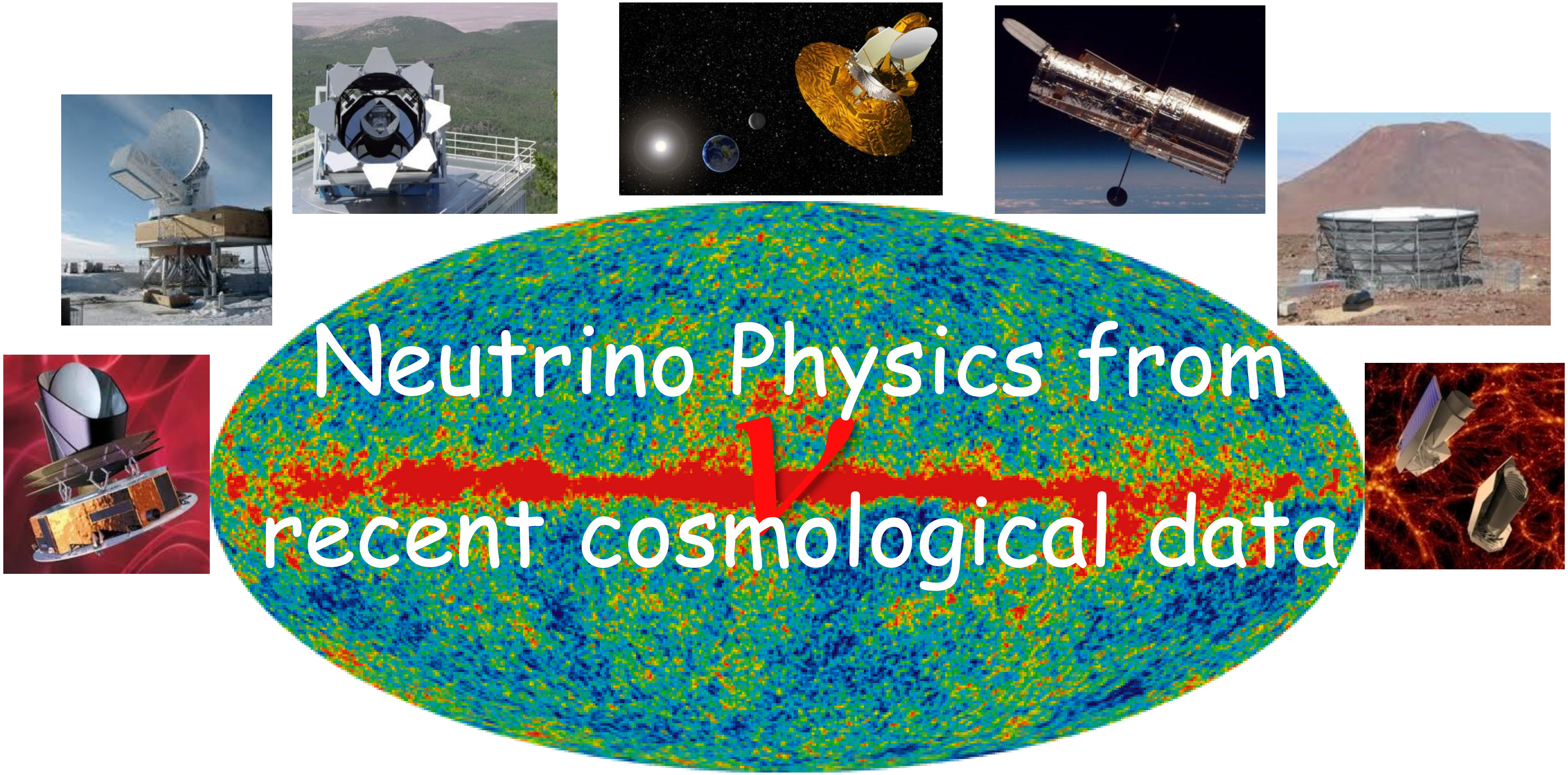

Neutrino Physics from recent cosmological data

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University of Rome "La Sapienza"

WHAT IS ν?: From new experimental neutrino results to a deeper understanding of theoretical physics and cosmology.
Florence, 24 June

Outline

- Cosmic Neutrino Background: Neutrino Mass and Neutrino Number

- Neutrino Mass effects on cosmological observables

- Model Dependence:

1. Reionization
2. Curvature

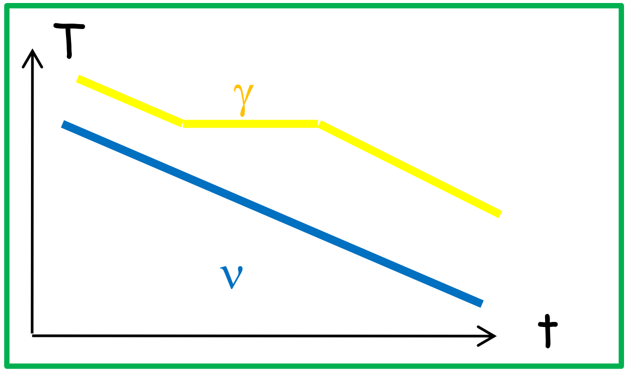
- Neutrino Number effects on CMB

- Model Dependence: Curvature

- Extra Dark Radiation

- Conclusions

Cosmic Neutrinos



Weak interactions in the primordial plasma:

$p + e^{-} \leftrightarrow n + \nu_e$ where $\Gamma = \langle \sigma_\nu n_\nu c \rangle$

When $\Gamma < H$ we have the neutrino decoupling

$$k_B T_{dec} = 1 MeV$$

$\boxed{2m_e}$

If the decoupling was istantaneous, we get:

$$T_\gamma / T_\nu = (11/4)^{1/3}$$

So nowaday $T_\nu = 1.95K$

$\boxed{e^{+}e^{-} \leftrightarrow \gamma\gamma}$

Cosmological standard value $N_{eff} = 3.\underline{046}$

(non-istantaneous decoupling)

$\boxed{e^{+}e^{-} \rightarrow \gamma\gamma}$

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

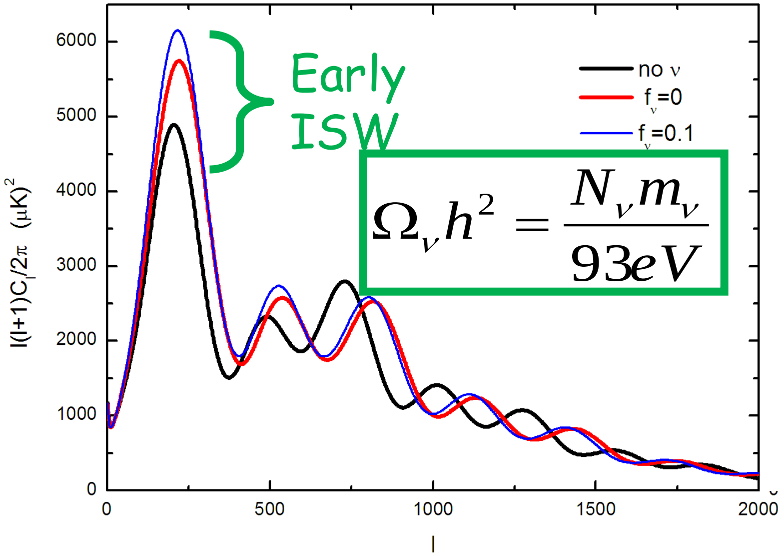
Cosmological constraints

$$\left\{ \begin{array}{l} \Omega_\nu h^2 = \dfrac{\Sigma_\nu m_\nu}{93 eV} \\[2ex] N_{eff} = 3 + N_{\nu s} \end{array} \right.$$

Cosmological constraints

$$\begin{cases} \enclose{circle}{\Omega_\nu h^2} = \dfrac{\Sigma_\nu m_\nu}{93 eV} \\ N_{eff} = 3 + N_{\nu s} \end{cases}$$

Probing the Neutrino mass with cosmological data



$$\boxed{\Omega_\nu h^2 = \frac{N_\nu m_\nu}{93eV}}$$

WMAP-7 $\sum m_\nu < 1.3eV$ (95% cl)

Assuming 3 degenerate neutrinos

Komatsu et al (2010)

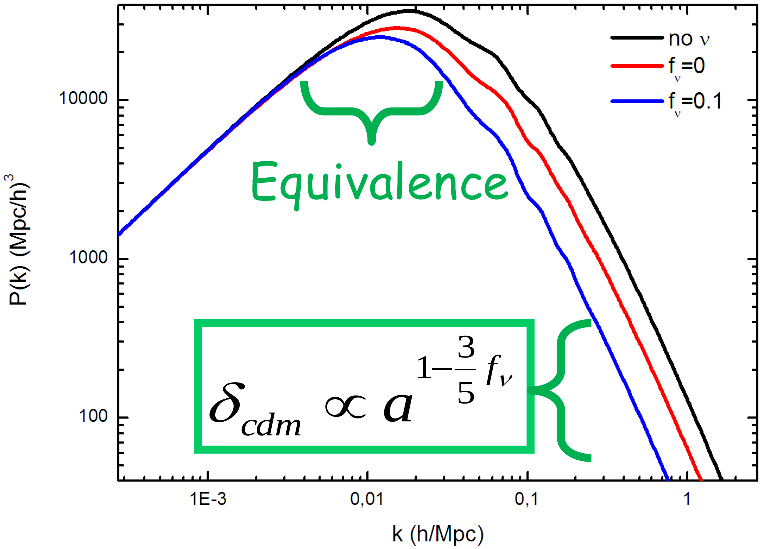
WMAP-7+H0+SDSS DR7

$\sum m_\nu < 0.44eV$ (95% cl)

Hannestad et al (2010)

Free-streaming: $\lambda_{FS} = 2\pi\sqrt{\frac{2}{3}}\frac{v_{th}}{H}$

$$v_{th} \approx 150(1+z)\left(\frac{1eV}{m_\nu}\right)km/s$$



$$\boxed{\delta_{cdm} \propto a^{1-\frac{3}{5}f_\nu}}$$

But, are these limits stable?!

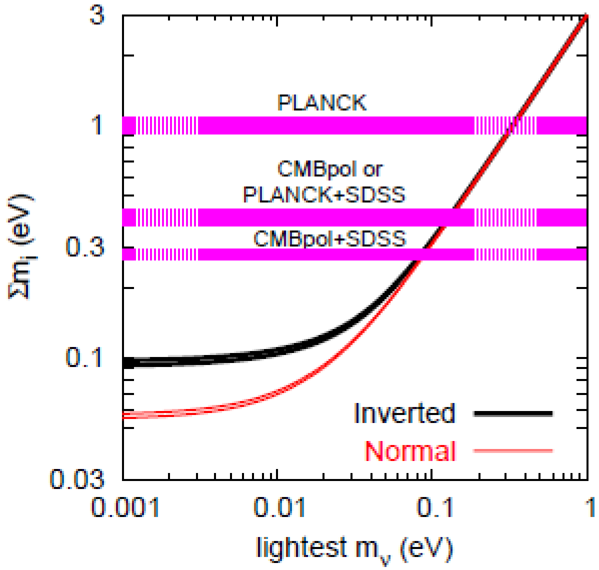
Current constraints

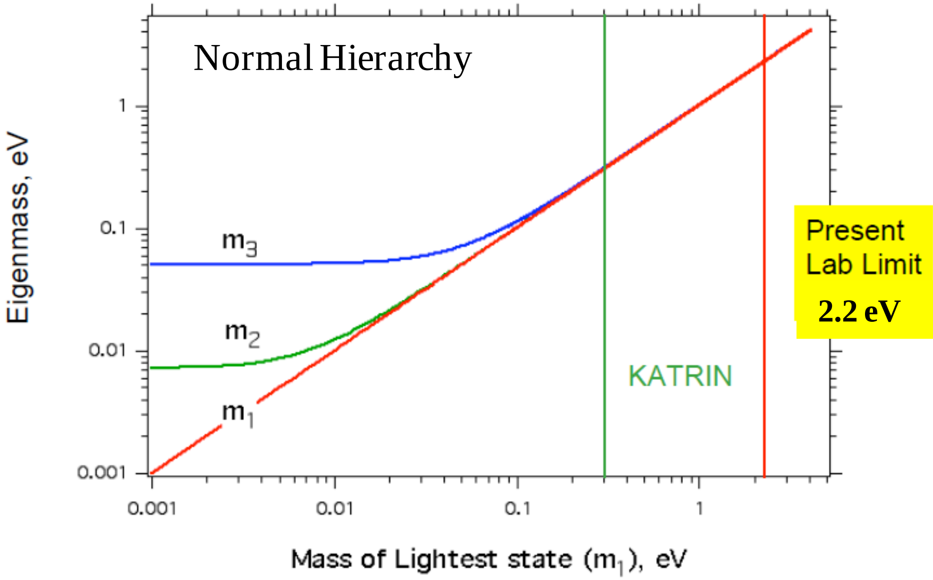
CMB + mpk (status) $\sum m_\nu < 0.44 eV$ model dependent!

Potential: Planck + Euclid $\sum m_\nu < 0.037 eV$

β-decay $m_\nu < 2.2 eV$ model independent

Potential: KATRIN $m_\nu < 0.2 eV$





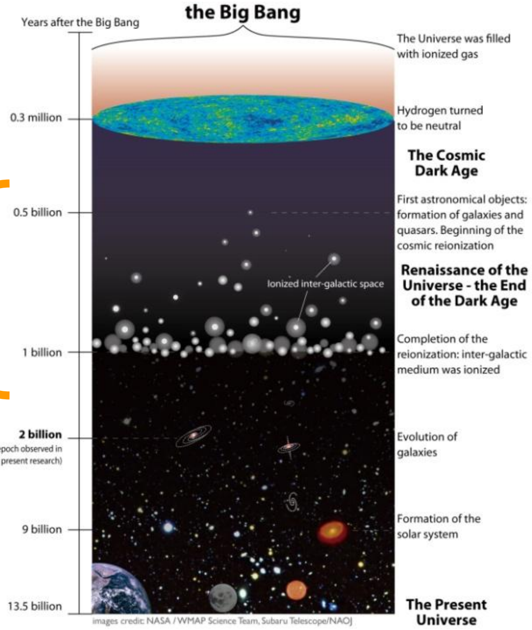
Present Lab Limit **2.2 eV**

Model dependence
Reionization

Quasar

Reionization
20>z>6

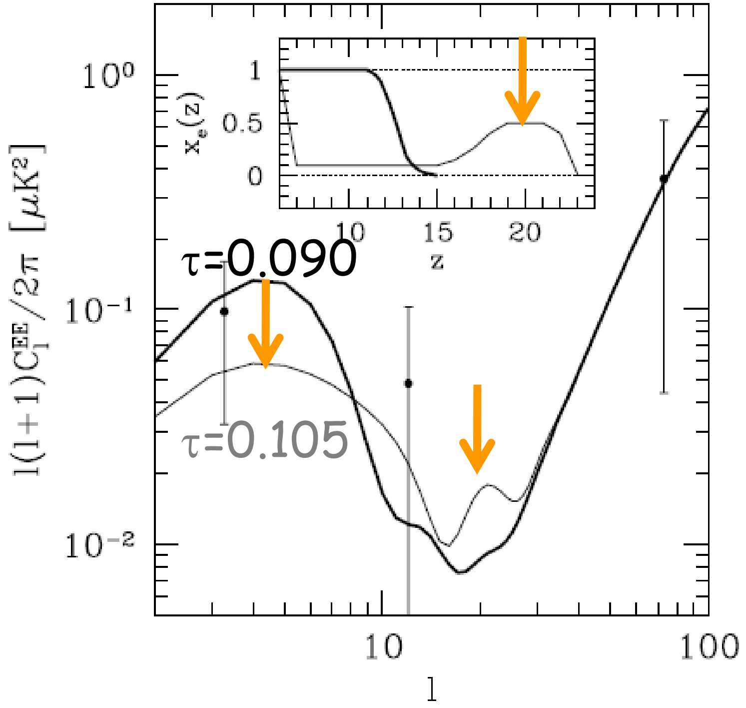
Gunn-Peterson
effect



Ionized
Universe
Neutral

Universe
Dark Age

Reionized
Universe



Sudden reionization
Double peak reionization

Mortonson & Hu (2008)

Results

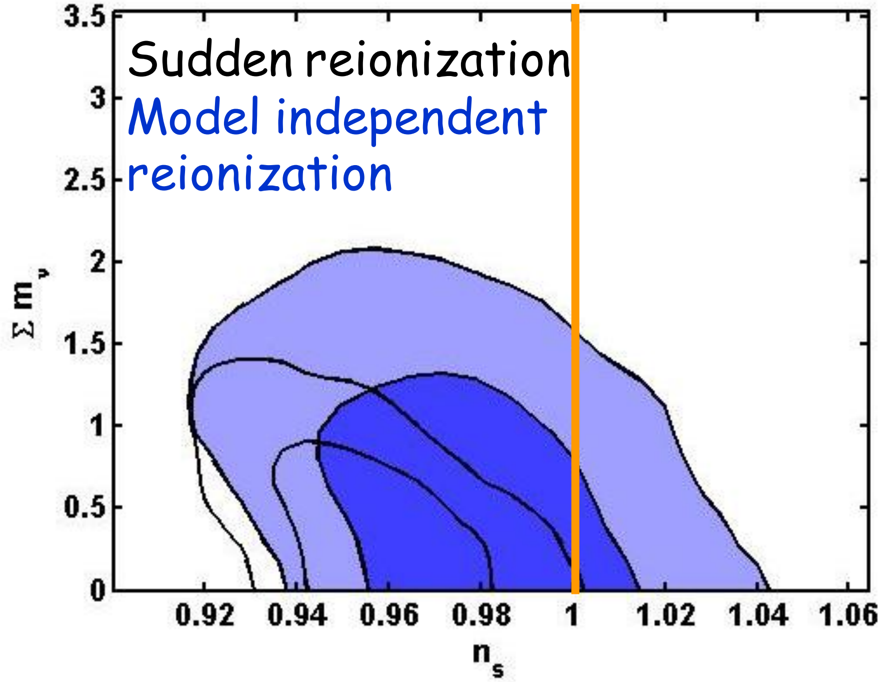
How do the constraints on the cosmological parameters (in particular on the neutrino mass) change, if, instead of using a sudden reionization model, we analyze the process of reionization through the Principal Components, making it independent from the model?

CosmoMC modifiyed to account for a model independent reionization with the first 5 PCs.

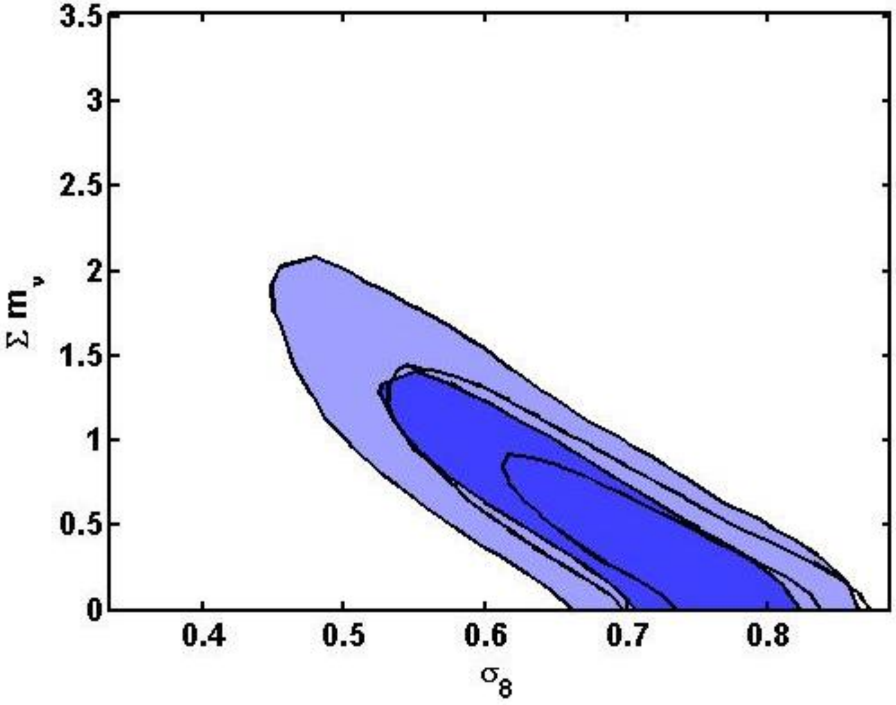
Parameters	**WMAP7 (Sudden reionization)**	**WMAP7 (model independent reionization)**
$\Omega_b h^2$	0.0221±0.0012	0.0226±0.0015
$\Omega_c h^2$	0.117±0.013	0.115±0.017
Ω_Λ	0.674±0.134	0.675±0.148
n_s	0.955±0.033	0.975±0.045
H_0	65.7±8.2	66.0±10.2
Σm_ν	<1.15eV(95%)	<1.66eV(95%)

Archidiacono et al., PRD (2010)

Degeneracies

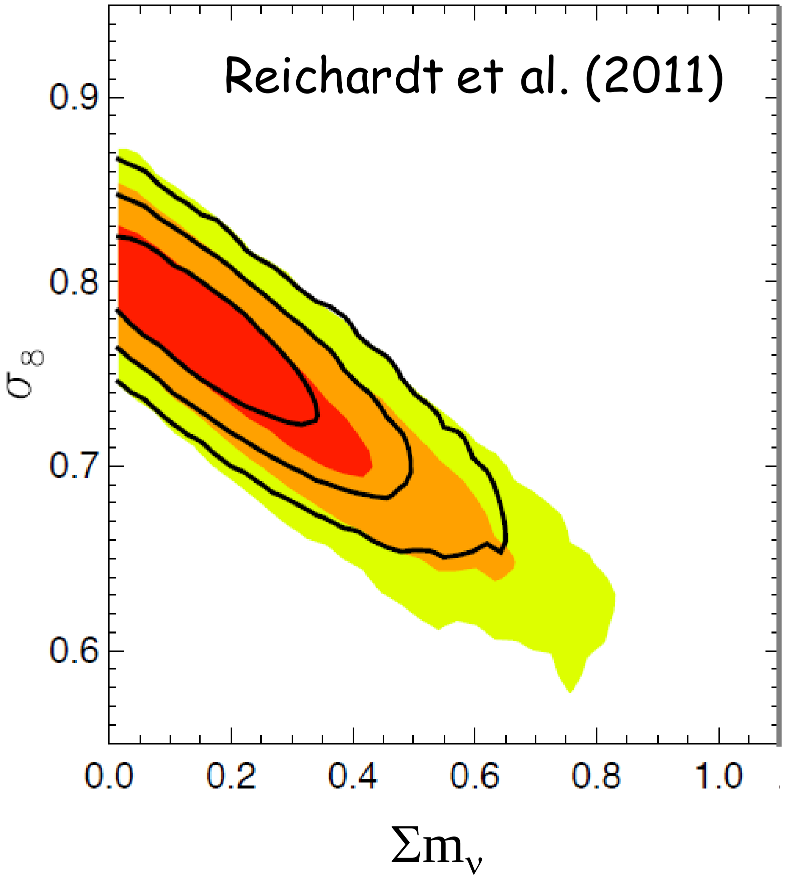


The model independent reionization agrees with the Harrison Zel'dovich primordial spectrum within 1σ



Archidiacono et al., PRD (2010)

tSZ and neutrino mass



$$D^{tSZ} \propto \left(\frac{h}{0.71}\right)^{1.7} \left(\frac{\sigma_8}{0.80}\right)^{8.3} \left(\frac{\Omega_b}{0.044}\right)^{2.8}$$

WMAP-7 + SPT + BAO + H_0
No tSZ subtraction:

$$\boxed{\sum m_\nu < 0.52 eV} \quad (95\%)$$

No modeling uncertainty:

$$\sum m_\nu = 0.29 \pm 0.10 eV$$
$$\sigma_8 = 0.732 \pm 0.017$$

(Seghal)

$$\sum m_\nu = 0.15 \pm 0.09 eV$$
$$\sigma_8 = 0.776 \pm 0.019$$

(Shaw)

50% modeling uncertainty:

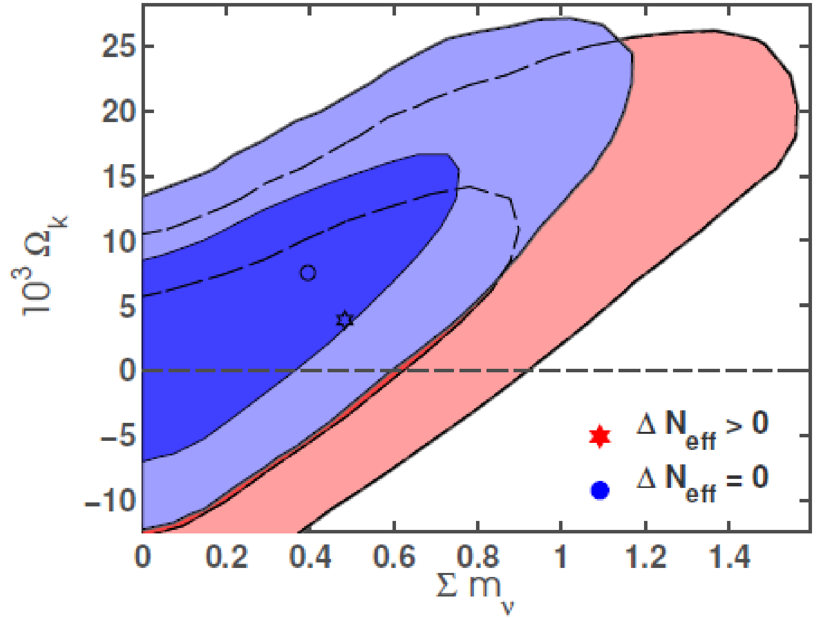
$$\boxed{\sum m_\nu < 0.40 eV} \quad (95\%)$$

Model dependence
Curvature

WMAP-7 + ACT + SPT + BAO + H_0

ΔN_{eff}	0	0	0.995±0.430
Σm_ν	<0.45 eV	<0.95 eV	<1.19 eV
Ω_k 10^3	0	7.52±7.74	3.46±8.69

The degeneracy considerably increases the uncertainty in the sum of neutrino masses.



Smith, MA et al., PRD (2012)

The number of effective relativistic degrees of freedom

$$\begin{cases}\Omega_\nu h^2 = \dfrac{\Sigma_\nu m_\nu}{93eV}\\ \boxed{N_{eff}} = 3 + N_{\nu s}\end{cases}$$

The total amount of relativistic degrees of freedom in the Universe is therefore parametrized in the following way:

$$\Omega_R h^2 = \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\Omega_\gamma h^2$$

A value of Neff > 3.046 is equivalent to the presence of a new «dark radiation» component :

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_M}{a^3}+\frac{\Omega_\gamma}{a^4}+\frac{\Omega_\nu}{a^4}+\Omega_\Lambda+\frac{\Omega_{DR}}{a^4}$$

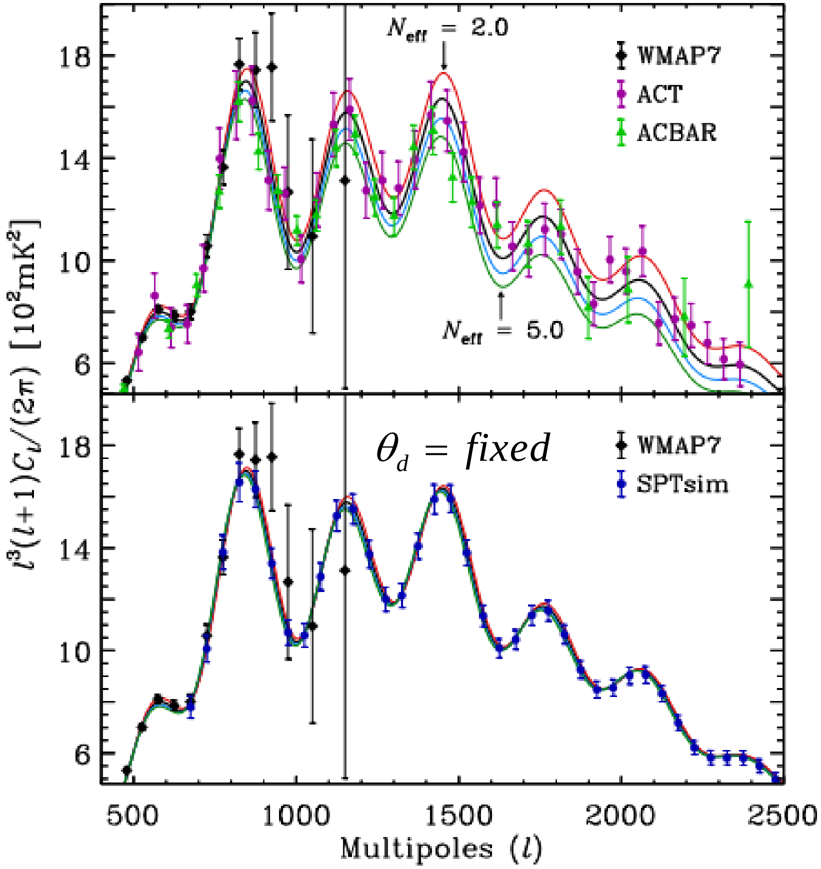
Probing the Neutrino number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the size of the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s}{a^2}\frac{da}{H}$$

and the damping at recombination:

$$r_d^{\,2} = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H}\left[\frac{R^2 + \frac{6}{15}(1+R)}{6(1+R^2)}\right]$$



Hou et al (2011)

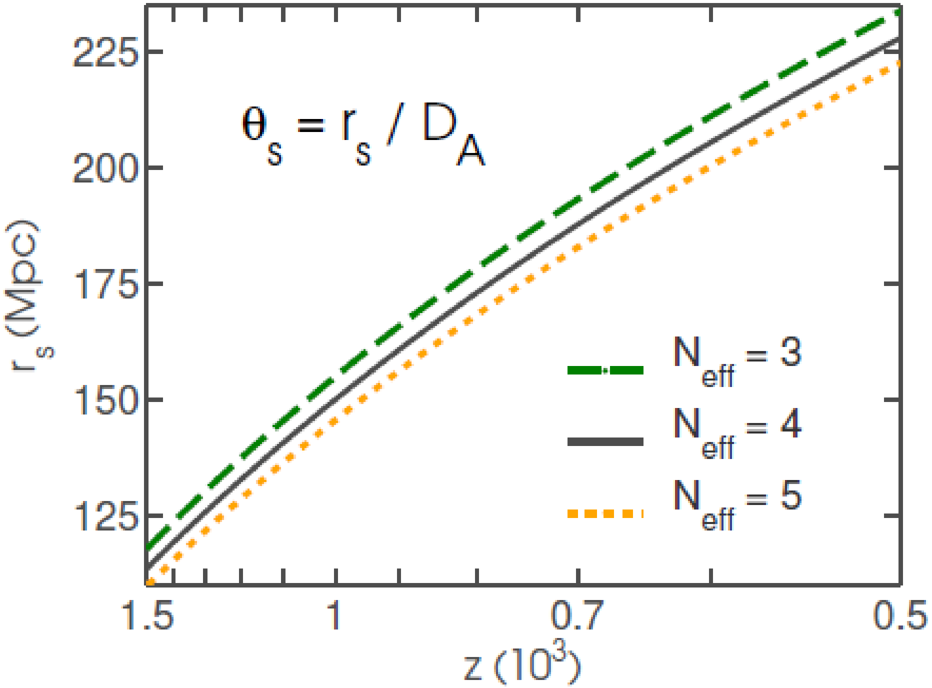
Moreover a larger neutrino number increases the early ISW as the neutrino mass .

Model dependence
Curvature

The size of the sound horizon $r_s \propto 1/H$

The damping $r_d \propto 1/\sqrt{H}$

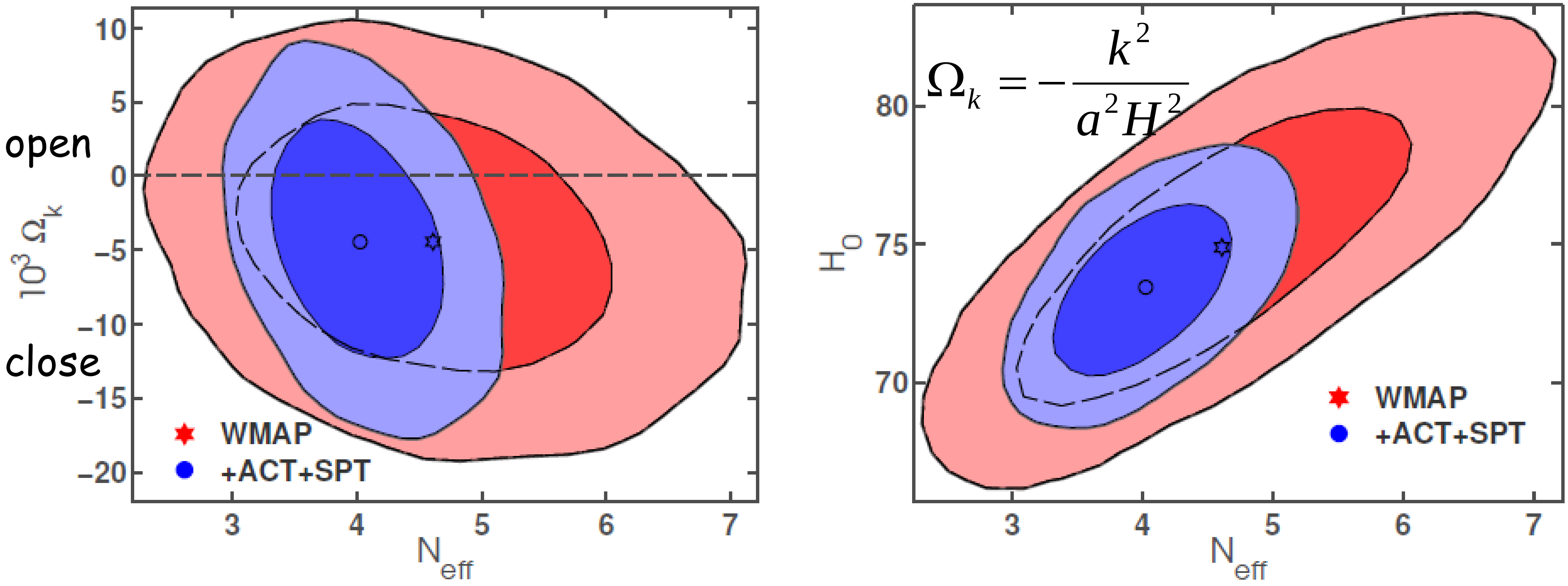
$$\boxed{\theta_s = \frac{r_s}{D_A}} \longrightarrow D_A \propto 1/H \longrightarrow \theta_d = \frac{r_d}{D_A} \propto \sqrt{H}$$



If Neff increases, we will expect a spatially close Universe

Smith, MA et al., PRD (2012)

Results and degeneracies



$$\Omega_k = -\frac{k^2}{a^2 H^2}$$

Even if the curvature is allowed to vary, the standard value of the number of relativistic degrees of freeedom is still disfavoured at 2 sigma c.l.

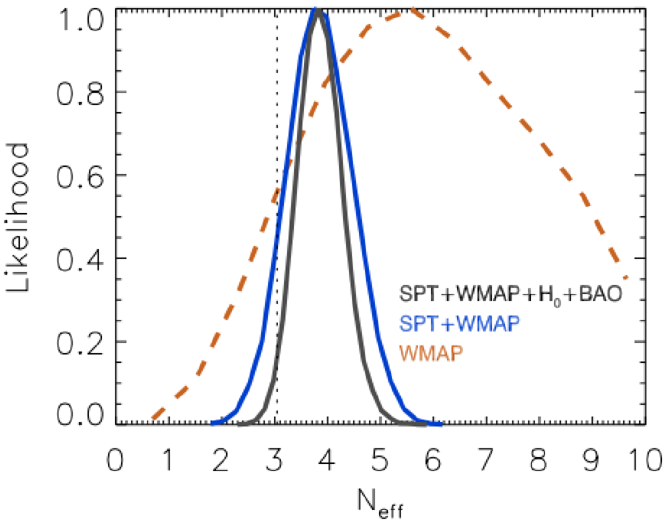
Smith, MA et al., PRD (2012)

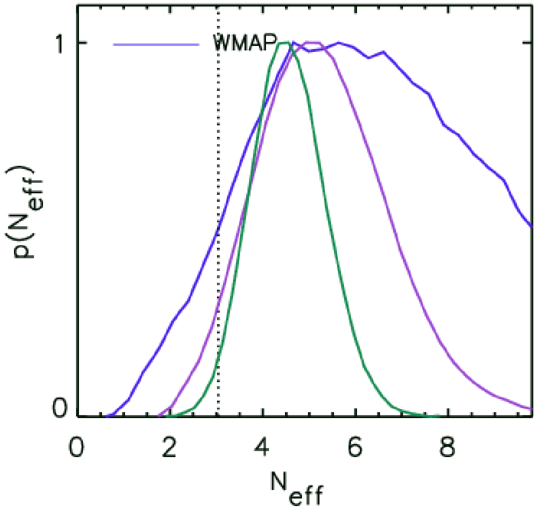
Hints for a Dark Radiation

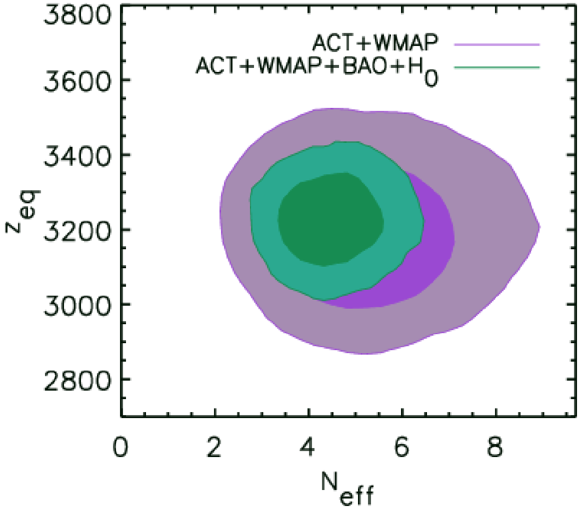
WMAP-7+SPT $N_{eff} = 3.85 \pm 0.62$

WMAP-7+SPT+BAO+H0 $N_{eff} = 3.86 \pm 0.42$

Keisler et al. (2011)







WMAP-7+ACT $N_{eff} = 5.3 \pm 1.3$

WMAP-7+ACT+BAO+H0 $N_{eff} = 4.8 \pm 0.8$

Dunkley et al. (2010)

What Dark Radiation is made of? Sterile Neutrinos?

Exotic models:

- gravitational waves
- axions
- decay of non-relativistic matter
- Early Dark Energy

Massless neutrinos equations of perturbations:

$$\left.\begin{aligned}
\dot{\delta}_\nu &= \frac{\dot{a}}{a}\left(1-\underline{3c^2_{eff}}\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - k\left(q_\nu + \frac{2}{3k}\dot{h}\right),\\
\dot{q}_\nu &= \underline{kc^2_{eff}}\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu - \frac{2}{3}k\pi_\nu,\\
\dot{\pi}_\nu &= \underline{3c^2_{vis}}\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right) - \frac{3}{5}kF_{\nu,3},\\
\frac{2l+1}{k}\dot{F}_{\nu,l} - lF_{\nu,l-1} &= -(l+1)F_{\nu,l+1}, \quad l \geq 3.
\end{aligned}\right\}$$

c^2_{eff} The effective sound speed

c^2_{vis} The viscosity parameter

If Dark Radiation is made of free-streaming particles,

$$c^2_{eff} = c^2_{vis} = 1/3$$

Results

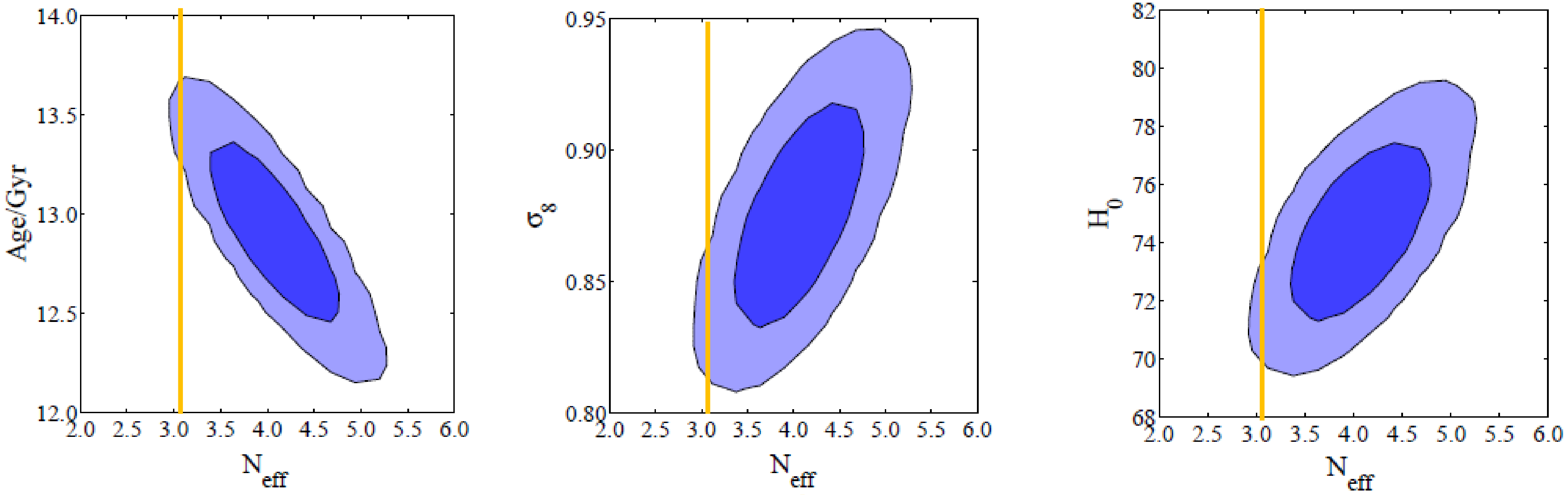
	$N_{eff}, c^2_{eff}, c^2_{vis}$	N_{eff}
N_{eff}	4.08 ± 0.71	3.89 ± 0.70
c^2_{eff}	0.312 ± 0.026	1/3
c^2_{vis}	0.29 ± 0.21	1/3

c^2_{eff} and c^2_{vis} consistent with 1/3

2σ evidence for $N_{eff} > 3.046$

Archidiacono et al., PRD (2011)

Cosmological parameters degeneracies



Extra Dark Radiation
12.8 Gyrs

Clusters and Ly-alpha surveys move to $N_{eff} = 3$

Archidiacono et al., PRD (2011)

Results

	$N_{\nu s}$, c^2_{eff} , c^2_{vis}	$N_{\nu s}$, c_{vis}	$N_{\nu s}$, c^2_{eff}, c^2_{vis}, Σm_ν
$N_{\nu s}$	1.10±0.79	1.46±0.76	1.12±0.86
c^2_{eff}	0.24±0.13	1/3	0.24±0.13
c^2_{vis}	<0.91 (95%cl)	<0.74 (95%cl)	<0.92 (95%cl)
Σm_ν	—	—	<0.79 eV (95%cl)

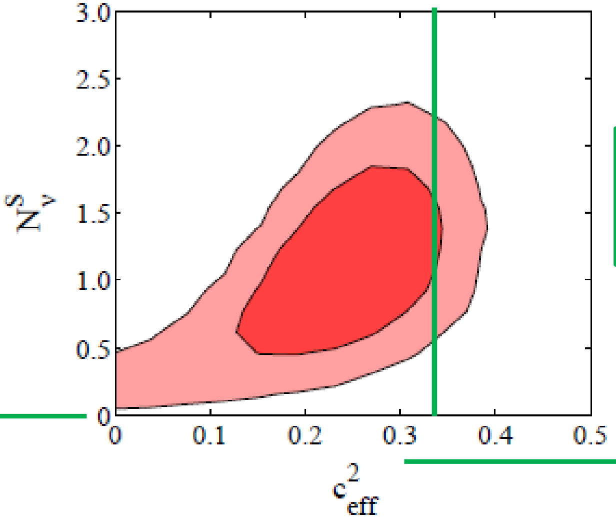
$N_{\nu s}$ detection at 2σ

c^2_{eff} and c^2_{vis}
consistent with 1/3 within 1σ

Archidiacono et al., PRD (2011)

Neutrino parameters degeneracies

$N_{\nu s}$ detection at 2σ



$c^2_{\rm eff}$
consistent with 1/3 within 1σ

We have found a 2σ evidence for Dark Radiation.
Moreover, the values we have got for the effective sound speed and viscosity speed are consistent with the value of 1/3 that a free-streaming relativistic component should have.
So sterile neutrinos are a good candidate for extra Dark Radiation.

Archidiacono et al., PRD (2011)

Conclusions

- Priors are important!

We investigated the influence of the theoretical assumptions on reionization and flatness on the cosmological neutrino mass bounds and on the effective number of relativistic degrees of freedom. The cosmological constraints on the neutrino masses are weakened if we parametrize the reionization process through the Principal Components or if we allow the curvature to vary.

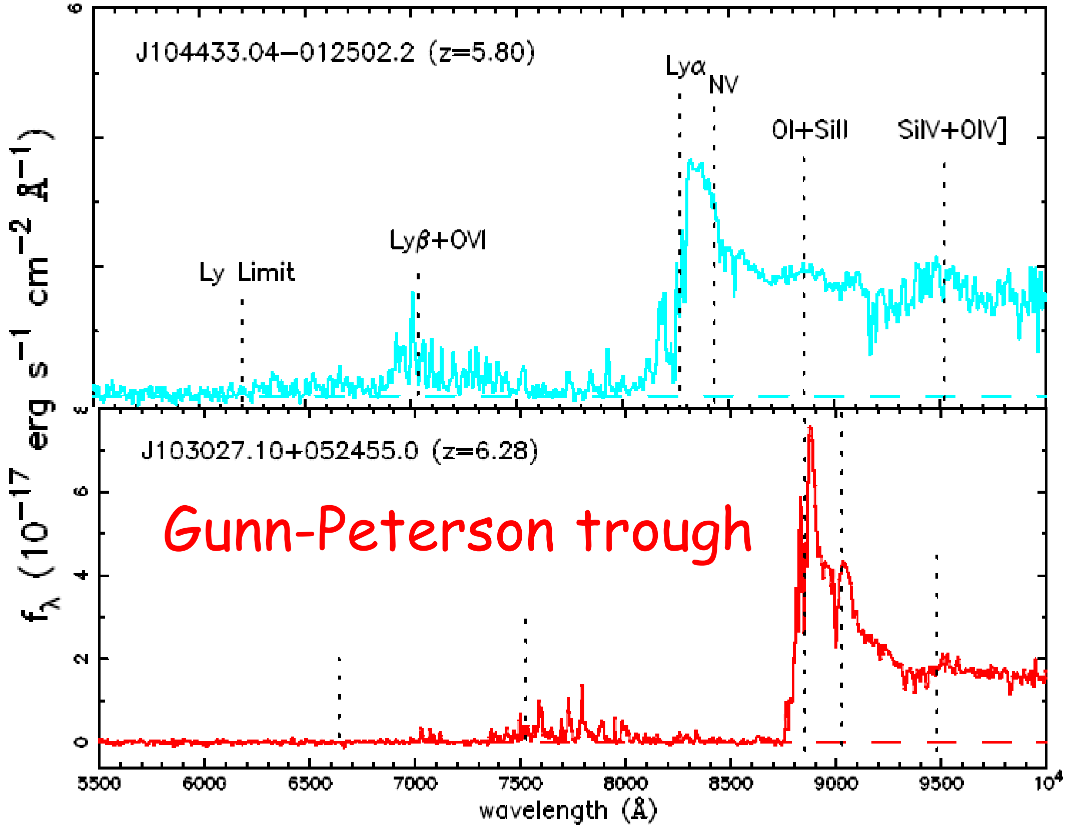
- Secondary Anisotropies and Foregrounds

An important issue is to obtain a perfect subtraction of foregrounds and a clear detection of Sunyaev Zel'Dovich effect, in order to measure the absolute neutrino mass scale with cosmological data.

Thank you for your attention!

The Gunn-Peterson effect

The Gunn-Peterson trough is a feature of the spectra of the quasars due to the presence of neutral hydrogen in the intergalactic medium. The trough is characterized by suppression of electromagnetic emission from the quasar at wavelengths less than that of Lyman alpha line at the redshift of the emitted light.



The effect has been observed only in the spectra of the quasars at z>6

"Evidence For Reionization at z ~ 6: Detection of a Gunn-Peterson Trough In A z=6.28 Quasar"Becker, R. H.; *et al.* (2001).

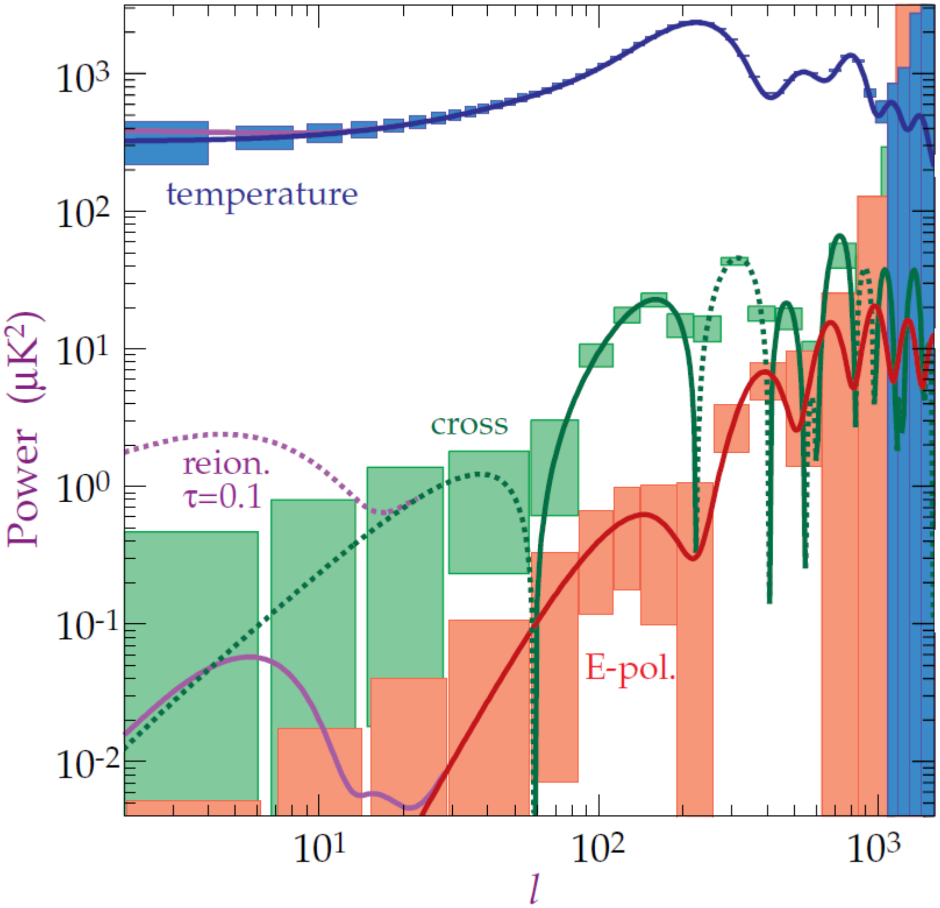
CMB and Reionization

Durig reionization the rescattering of photons suppresses the anisotropies on angular scales below the horizon at the rescattering epoch by a damping factor $\exp(-\tau_{reion})$ where

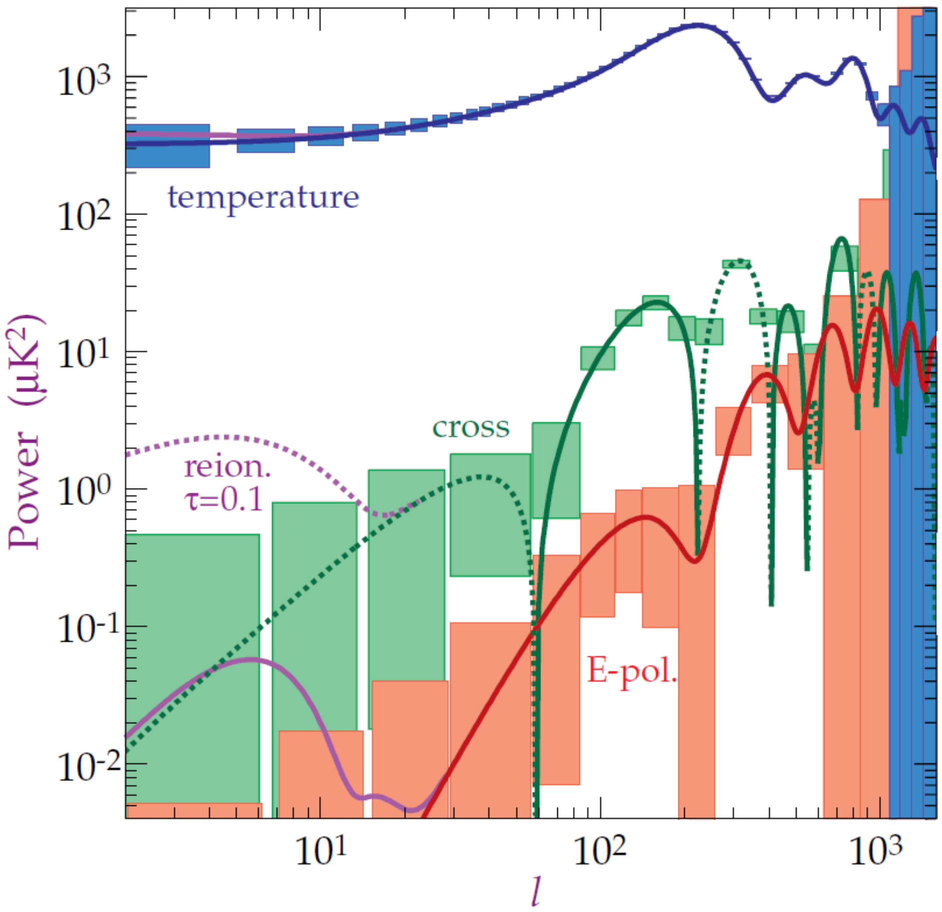
$$\tau_{reion} = c\,\sigma_T \int dt\, n_e\,(1+z)^3$$

The uniform reduction of power at small scales has the same effect as a change in the overall normalization.

Moreover at l<30 the observations are limited by "cosmic variance". So you cannot see reionization effects in temperature spectrum.



CMB and Reionization



Instead you can clearly recognize reionization effects in the polarization spectrum at l<30.

Infacts, CMB photons cannot spread themselves on such large scales before the recombination has ended. The polarization signal is expected to be zero at low l. So the peak at low l is due to the rescattering of CMB photons during reionization.

arXiv:astro-ph/9706147v1

A CMB Polarization Primer

Wayne Hu and Martin White

Principal Components

$$N_z + 1 = (z_{MAX} - z_{min})/\Delta z \begin{cases} z_{min} = 6 \text{ (QSO)} \\ \Delta z = 0.25 \text{ (}\Delta z \rightarrow 0\text{ results indipendent of the bin)} \\ z_{MAX} = 30 \\ N_z = 95 \end{cases}$$

PCs: Fisher matrix eigenfunctions

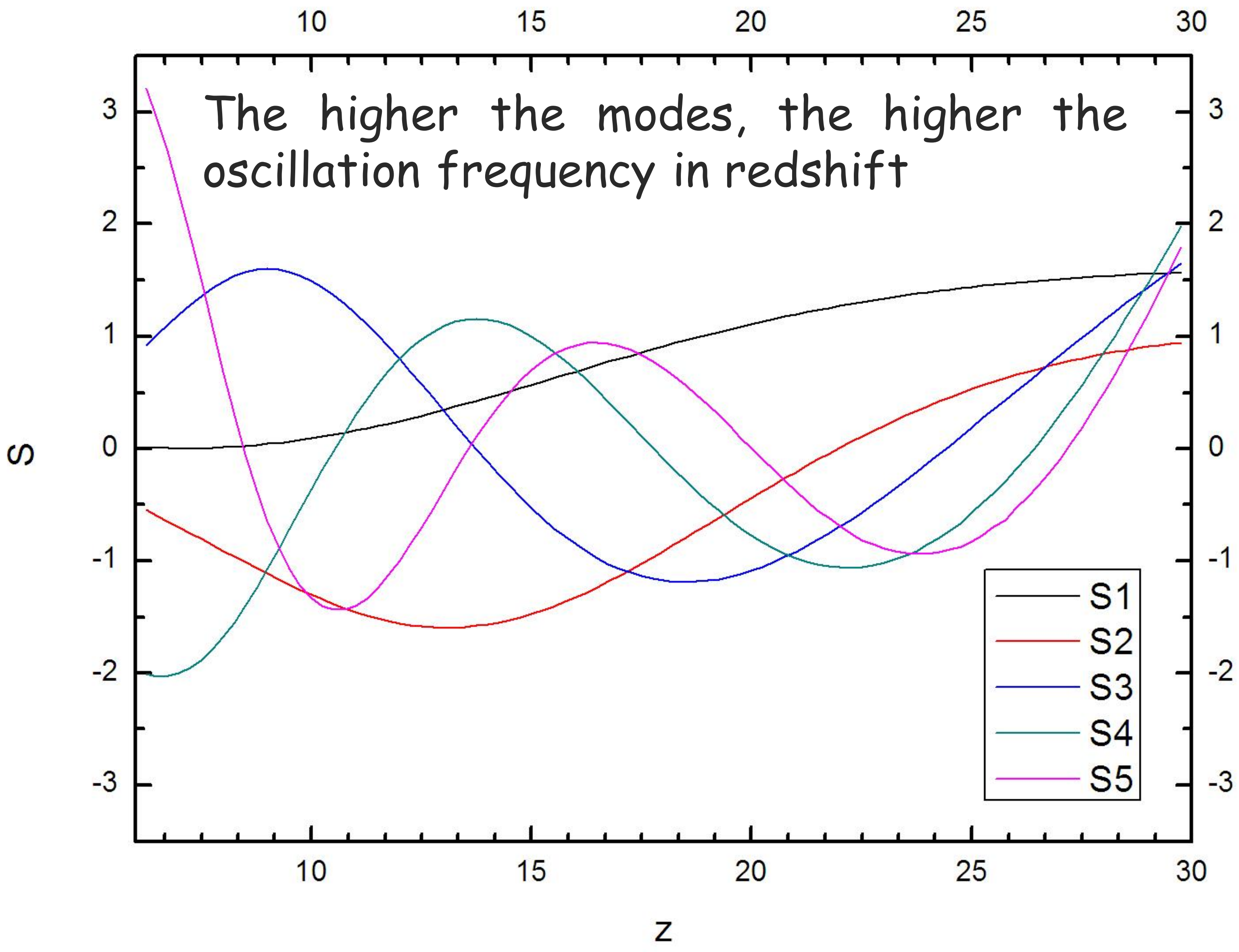
$$F_{ij} = \sum_{l=2}^{l_{MAX}} \left(l + \frac{1}{2} \right) \frac{\partial \ln C_l^{EE}}{\partial x_e(z_i)} \bigg|_{x_e^{fid}(z_i)} \frac{\partial \ln C_l^{EE}}{\partial x_e(z_j)} \bigg|_{x_e^{fid}(z_j)}$$

l_{MAX} = 100 (beyond the effects are negligible), $x_{e,fid}$ = 0.15 (not important)

$$F_{ij} = (N_z + 1)^{-2} \sum_{\mu=1}^{N_z} S_\mu(z_i) \sigma_\mu^{-2} S_\mu(z_j)$$

σ_μ^2 PC variance $\qquad \sigma_\mu^2 < \sigma_{\mu+1}^2$

Principal Components



The higher the modes, the higher the oscillation frequency in redshift

Principal Components

The PCs satisfy the orthogonality and completeness relations

$$\int_{z_{\min}}^{z_{MAX}} dz S_\mu(z) S_\nu(z) = (z_{MAX} - z_{\min})\delta_{\mu\nu}$$

$$\sum_{\mu=1}^{N_z} S_\mu(z_i) S_\mu(z_j) = (N_z + 1)\delta_{ij}$$

Any reionization process can be decomposed in PCs

$$x_e(z) = x_e^{fid}(z) + \sum_\mu m_\mu S_\mu(z)$$

The mode amplitudes are

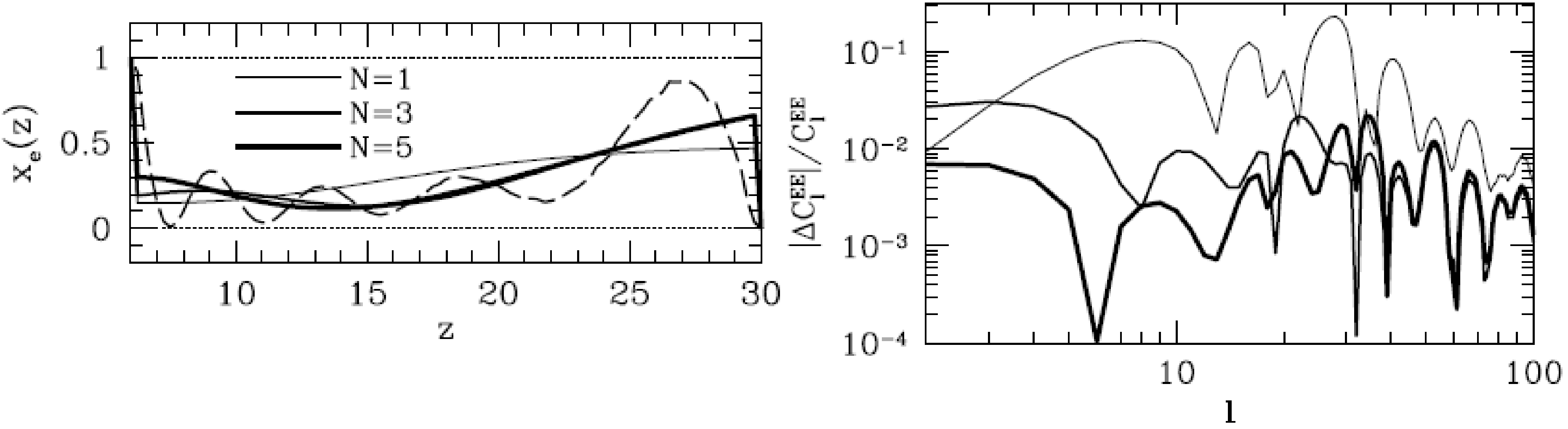
$$m_\mu = \frac{1}{z_{MAX} - z_{\min}} \int_{z_{\min}}^{z_{MAX}} dz S_\mu(z) \delta x_e(z)$$

Any reionization process between zMAX and zmin is fully described by a set of mode amplitudes.

Utility

The first 3-5 modes provide all the informations about reionization that are relevant in the E mode polarization spectrum at larger scales. The higher mode oscillations in redshift at higher frequency can be mediate to zero.

NB: This is not true for the whole reionization process.



The default case is with 10 PCs

Caveat: the physical consistence

The constraints on the fraction of ionized hydrogen $0 \le x_e \le 1$ are not built in to the method.
A necessary but not sufficient condition is:

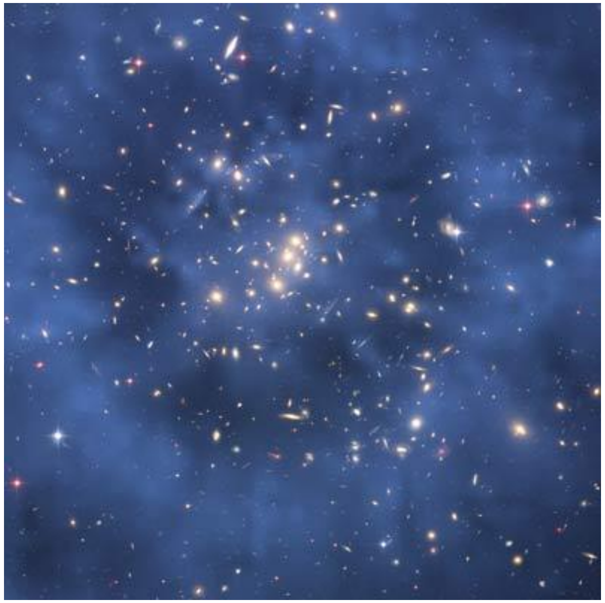
$$\sum_{\mu} m_{\mu}^{2} \le f$$

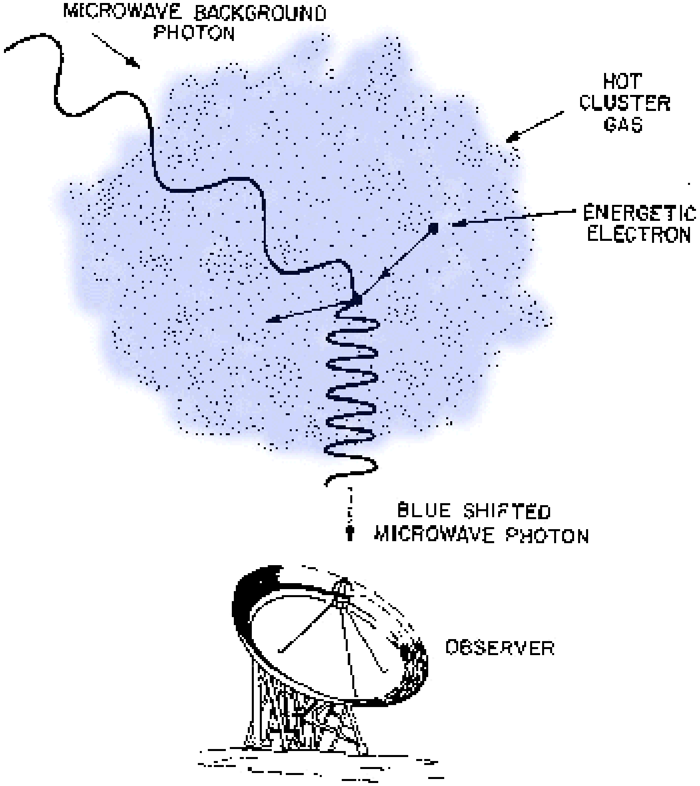
where

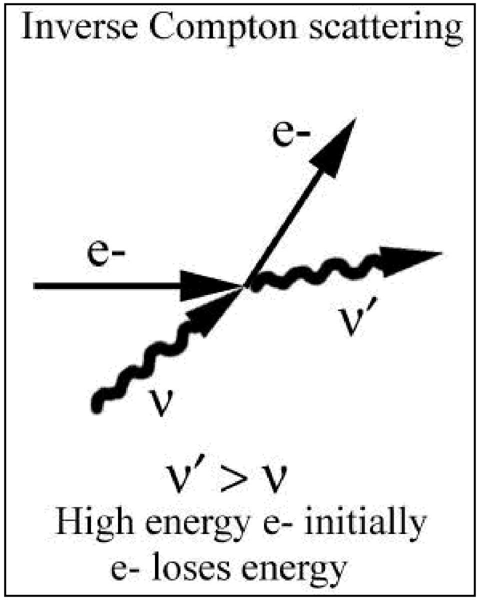
$$f \equiv \max\left[\left(x_e^{fid}\right)^2, \left(1 - x_e^{fid}\right)^2\right]$$

It's important to notice that the higher modes have a great effect on $x_e(z)$, while they are irrelevant for the polarization spectrum.

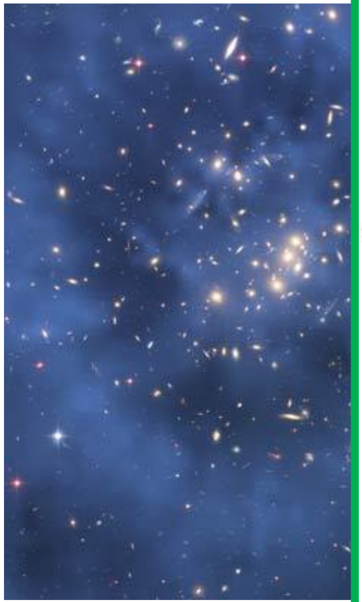
Effetto Sunyaev Zel’dovich

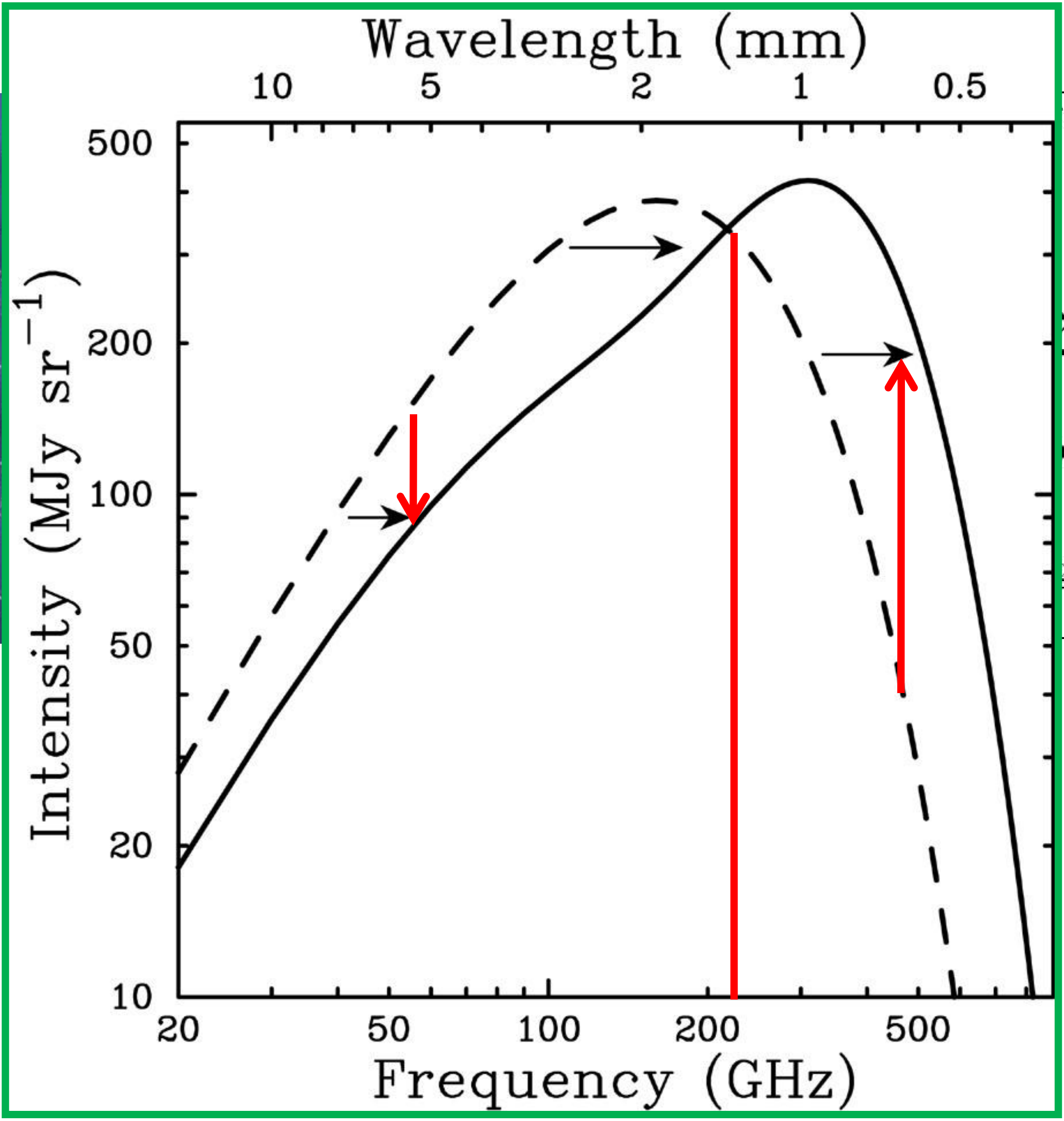


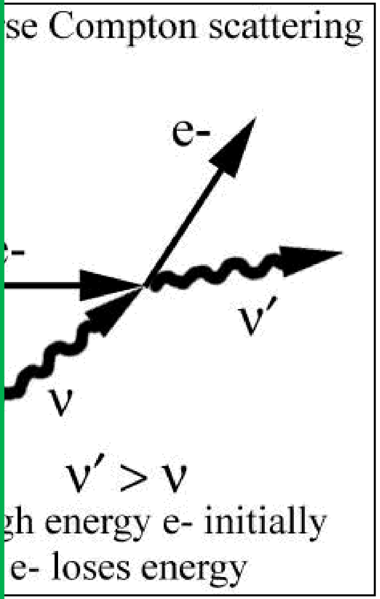




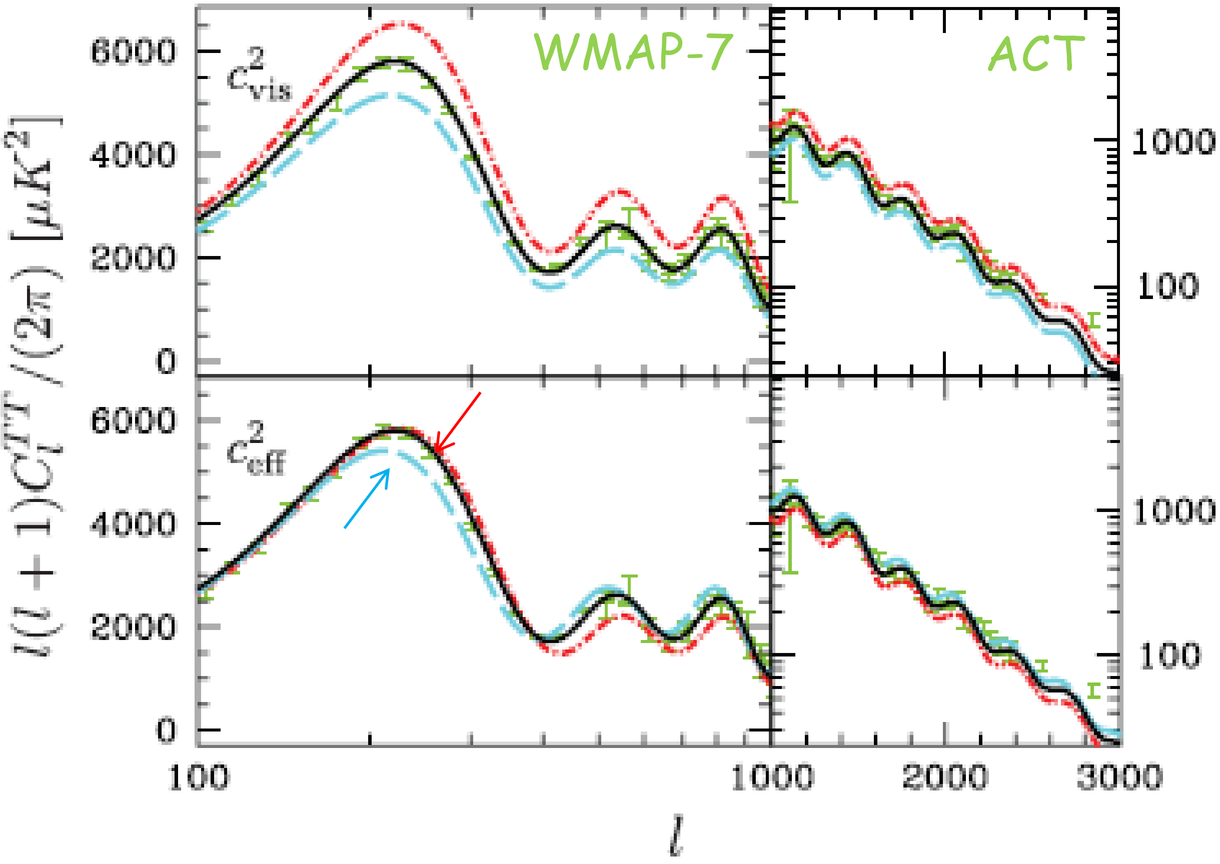
Effetto Sunyaev Zel’dovich







Effective sound speed and viscosity speed



$$c^2_{eff} = c^2_{vis} = 1/3$$

$$c^2_{eff} = 1/3,\ \ c^2_{vis} = 0$$

$$c^2_{eff} = 1/3,\ \ c^2_{vis} = 1$$

$$c^2_{eff} = 0.2,\ \ c^2_{vis} = 1/3$$

$$c^2_{eff} = 0.7,\ \ c^2_{vis} = 1/3$$

If Dark Radiation is made of free-streaming particles,

$$c^2_{eff} = c^2_{vis} = 1/3$$

Hu (1998), Smith et al. (2012)